The new generation of autonomous star trackers

Allan Read Eisenman[1] and Carl Christian Liebe[2]
Jet Propulsion laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena, CA 91109-8099, USA

John Leif Jorgensen[3]
Department of Automation, Building 327
Technical University of Denmark, 2800 Lyngby, Denmark

ABSTRACT

The most accurate instrument for spacecraft attitude determination is a star tracker. Generally, these are CCD-based instruments. Until recently, only first-generation units were available. However, these first-generation designs are limited to outputting positions of a few stars in sensor-referenced coordinates and require extensive external processing. Fortunately, advancing technology has enabled the development of a new second-generation class of star trackers. These designs are fully autonomous, solve the lost-in-space problem, have large internal star catalogs, use many stars for each data frame, have higher accuracy, smoother and more robust operation, potentially lower cost, and output attitude which is referenced directly to inertial space without any further external data processing. Two currently available designs which are in production and meet these requirements are the AST-201 from Lockheed Martin Missile & Space and the ASC from the Technical University of Denmark. The first design is in the general size, power, mass, and reliability class of typical, conventional star trackers. The second one features reduced size, power, mass, and cost, with commercial off-the-shelf components. Second-generation star trackers have a promising future with a likely evolution to low cost, miniature, stock instruments with wide application to a growing variety of space missions.

1. INTRODUCTION

It is vital for most space vehicles to know their attitude from an onboard sensor. The information is used to navigate, fire thrusters, and to point antennas and experiments, etc. Usually, a quaternion or a direction cosine matrix is used to represent the attitude of the vehicle. These describe a rotation from an inertial space coordinate system to a coordinate system referred to the attitude sensor. A successive coordinate rotation can relate the attitude sensor coordinate system to the spacecraft body in yaw, pitch, and roll. Specifically, the attitude determination subsystem has to derive the direction cosine matrix A which satisfies equation (1).

$$\hat{W} = A\hat{V} \tag{1}$$

where W is a unit vector in the sensor coordinate system and V is the same vector in the inertial coordinate system. Commonly, some combination of magnetometers, star trackers, sun sensors, zero crossing magnetometers, horizon sensors, or star scanners are used on both spin stabilized and three-axis stabilized spacecraft for attitude determination [1]. Star trackers are best suited for three-axis stabilized applications, In most applications the output of the star tracker is used to update and correct drift in an inertial reference system which provides high bandwidth positional information. However, a 'gyroless' spacecraft can use a mathematical model for attitude information. The star tracker then updates the state vector in this model.

[1] email: allan.eisenman@jpl.nasa.gov; (818) 354-4999
[2] email: carl.c.liebe@jpl.nasa.gov; (818) 354-7837
[3] email: jlj@iris.iau.dtu.dk; telephone +45 45 25 3448

Figure 1 shows an example of relating inertial space to a vehicle. An inertial coordinate system could be defined as the X-axis towards the Vernal equinox, the Z-axis toward the North pole of the celestial sphere, and the Y-axis pointing opposite the cross product 0! the two vectors.

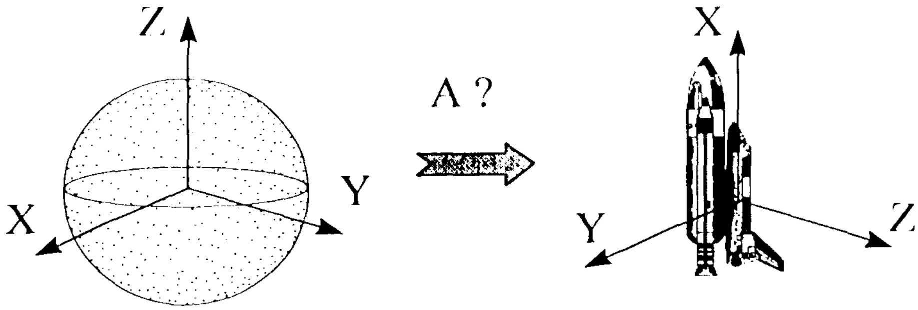

Figure 1. Relation between the celestial sphere and a spacecraft referenced coordinate system

2. FI1?ST-GENERATION CCD STAR TRACKERS

Attitude determination based on the use of charge couple devices (CCD) area array imaging sensors was pioneered in the early 1970s at JPL [2]. The instrument consists of a CCD sensor, associated optics, and dedicated electronics. Typically, two to six star images are detected in each data frame. The instrument then outputs the CCD coordinates of these bright spots, which are then utilized in the satellite main computer or in later post processing of the data on ground. The attitude determination may require additional information, such as the sun vector. Many commercial suppliers have implemented such star trackers [3- 7]. They can be characterized as first-generation units. Figure 2 shows the early, JPL, high-accuracy, ASTROS design [8] with key parameters of it given in Table 1.

Figure 2. JPL ASTROS star tracker of 1985, processing electronics on the left, camera head on the right.

Table 1. ASTROS key parameters

Mass	41 kg	Number of stars tracked	1-3
Power consumption	43 **W**	Initial attitude acquisition	**No**
Field **of View**	2.2 x 3.3 degrees	Update rate	**6 [[7**
Relative **Accuracy**	**0**.8 arcsec, 1 σ, I axis, per star	Thermal electric cooler	**Yes**

The Lawrence Livermore, National laboratory, Clementine star tracker deserves special mention as an early autonomous design which helped pave the way for true second-generation units. It featured a small carom head of about 450 g mass with a power consumption 01 about 4.5 watts, a very wide FOV of about 55 by 45 degrees, an innovative, spherically curved focal plane lens which was coupled to a Thompson CCD by a dual, field-flattening, fiber-optic plug system. It relied on the use of an external tracker software system called Stellar Compass ™ by its developer, Intelligent Decisions, Inc., which could track up to 10 stars from a small catalog ot' about 400 stars. Due to various factors, its accuracy and its sky coverage in roll angle were limited to the milliradian and 85° o ranges, respectively [9]. A successor model with improved performance characteristics is being manufactured by OCA Corp. of Garden Grove, California.

.3. SECOND-GENERATION CCD STAR TRACKERS

Within the last five years, a new generation o! star trackers has been developed. "1 hese are identified as second-generation units. This new generation of star (rackers is different from the prior generation because:

- Star constellation pattern recognition is performed autonomously utilizing internal catalogs. The solution of the Iost-in-space problem is inherent and no external processing nor additional attitude knowledge is needed for celestial pointing reference determination.

- Utilization of a large number of stars in the range of 25 to 85 in the field of view (FOV) is done for each data frame. Attitude determination from internal catalogs of over 20.000 stars is based on a signal which is effectively much larger than in first-generation units. This significantly improves acquisition probabilities and accuracy over the whole sky.

- All compensations, including light time effects, as they apply, are performed internally.

- Attitude quaternions referenced to inertial space are output directly without the intervention of external processing.

This recent development has been primarily facilitated by the availability of very powerful microprocessors (> 10 MIPS) and large memory (Mbytes) for spacecraft use. A significant advantage of a second-generation star tracker is the simplicity of its integration with the spacecraft. The instrument is completely stand-alone and autonomous, only a very simple, low bandwidth data interface exists between the satellite main computer and the star tracker. The savings in spacecraft integration by not having the attitude control computer include star catalogs and all of the associated processing and correction algorithms (thousands of lines of source code) are significant, and can be a major fraction of the cost of the tracker, itself. Additionally, the lengthy experience gained during development and test flights helps to assure a high level of reliability and robustness.

Figures 3 and 4 show two typical examples of second-generation star trackers [10, I I] with key parameters given in Tables 2 and 3.

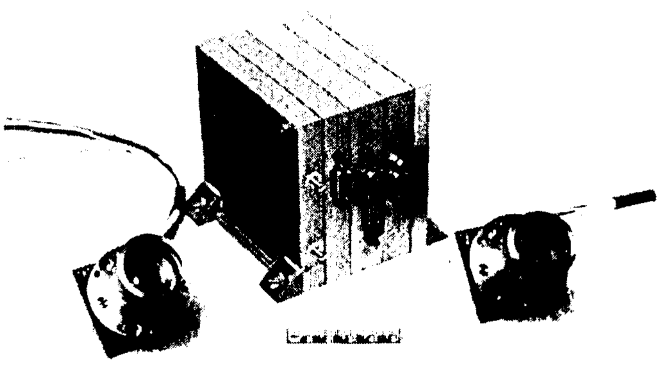

Figure 3. CHAMP ASC are used on the German CHAMP mission: a second-generation star [racker manufactured by the "1'ethnical University of Denmark, I 997. Data Processing Unit (DPU) is displayed with two separate camera heads.

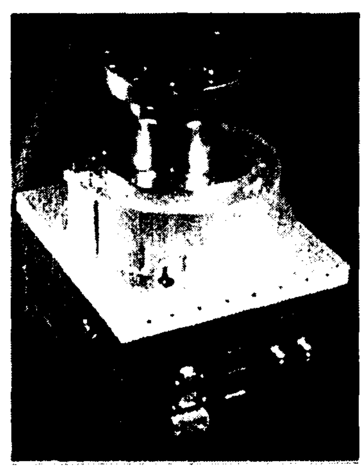

Figure 4. AST-201 are used on the New Millennium DS1 mission: a second-generation star tracker manufactured by Lockheed Martin Space and Missile Systems, 1997.

Table 2. CHAMP ASC key parameters

Mass	900 g
Power consumption	5 W
Field of View	19°x 14°
Relative Accuracy	3 arcsec, 1 σ, single axis
Number of stars tracked	25–200
Initial attitude acquisition	Yes
Update rate	1-4 Hz
Thermal electric cooler	No

Table 3. AST-201 key parameters

Mass	5.0 kg (with 18° baffle)
Power consumption	14 W at 25°C
Field of View	8.8° x 8.8°
Relative single axis accuracy	3 arcsec, 1 σ at 2 Hz
Stars tracked	9-49
Initial attitude acquisition	Yes
Update rate	5 Hz
Thermal electrical cooler	Yes

4. INITIAL ATTITUDE ACQUISITION

The initial attitude acquisition, or pattern recognition of star constellations, is not a trivial matter. The problem is illustrated in Figure 5. The second-generation star tracker is presented with an image of a small portion of the night sky (less than 10/o). The image includes uncertainties in the magnitude and in the positions of the stars. Also, false objects may be present in the image (planets, other satellites, radiation, etc.). The star tracker is required to complete the task in a few seconds.

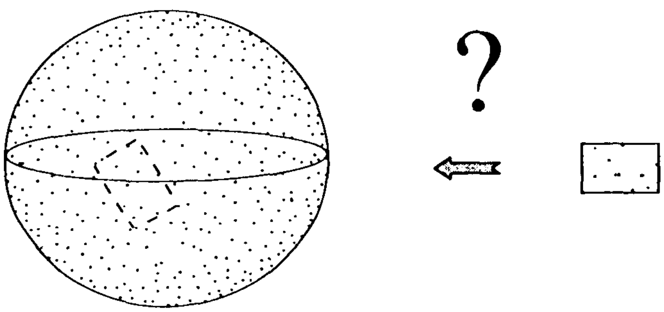

Figure 5. Performing pattern recognition of a star constellation.

The problem has been solved in different ways. Neither a comparison nor a detailed description of the various approaches will be given here. These algorithms are covered in numerous, detailed papers on pattern recognition of star constellations [12-21]. Usually, the algorithm will complete the pattern recognition in seconds with a success rate approaching 100’?4o. Pattern recognition has been demonstrated down to an FOV on a few degrees.

5. STAR TRACKER CHARACTERISTICS

A summary of selected characteristics of star trackers and their effects on design parameters are as follows:

5.1 Field of view

The size of the FOV is probably the most important parameter of a star tracker. General purpose star trackers FOVs range from a few degrees to over 30° diagonally. When the FOV is narrowed, the following will happen:

- The angular resolution ofa single pixel will be better, resulting in linear increase irr pitch and yaw accuracy.

- The performance will tend to improve, but roll, or twist accuracy will tend to remain constant

- '['he lens aperture will increase because it is desirable to have a given average number of stars in the FOV, to compensate for the narrower FOV in order to allow the star [racker to see fainter stars. This, with the increasing length of the optics, tends to increase the mass by the cube of the focal length (for a fixed f/no refractive design).

- The number of stars in the catalog must increase with the collecting aperture of the lens. This means that the complexity of the pattern recognition of star Constellations increases rapidly with the number of stars.

5.2 Sky coverage

Sky coverage is the percentage of the sky over which the star tracker will acquire and track. A second-generation star tracker has high sensitivity, resulting in a large number of stars being detected in the FOV. It will rarely experience "black outs" during tracking. The initial attitude acquisition is more difficult than tracking. When the number of stars in the FOV is small, the algorithms will tend to reject the image. This problem is aggravated by an acquisition catalog which is smaller than the full tracking catalog. Consequently, the minimum number of stars in one frame may drop below the minimum necessary for acquisition over a small percentage of the sky.

5.3 Mass

The mass of a star tracker is especially important to an increasing market for microsatellites. The mass of a star tracker varies from a few hundred grams to more than 20 kg. Mass is dominated by two components: the processing electronics and the optics. With the current state of technology, the mass of the electronics usually dominates the optics. However, as discussed later, when it is possible to implement a star tracker on a few integrated circuits (Ics), the mass of the optics will dominate, giving a decided advantage to a wide FOV design, as detailed above.

5.4 Star catalog size

The required size of the star catalog depends on the sensitivity of the system. If the system is sensitive (i.e., large aperture, long exposure time, etc.), a large star catalog is required. Figure 6 illustrates the required star catalog size as a function of the F'OV for 3, 15, and 75 average stars in the FOV.

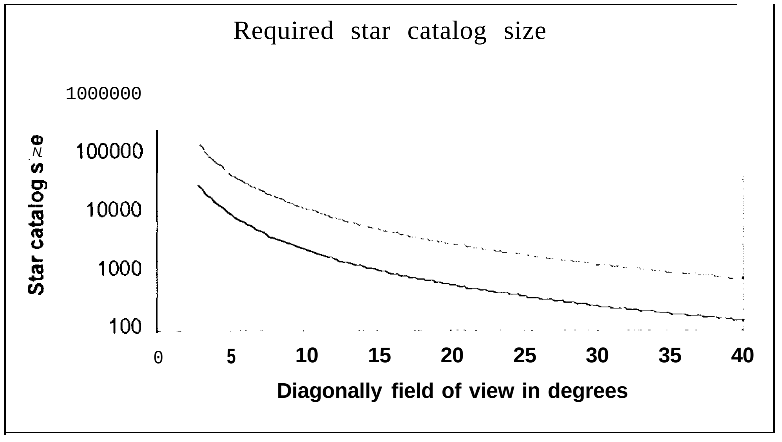

Figure 6. Required star catalog size as a function of the FOV for 3, 15, and 75 average stars in the FOV.

[t is undesirable to have a large star catalog, since it occupies large amounts of nonvolatile memory, and it complicates the initial attitude acquisition. The required processing power will increase rapidly with the number of stars.

5.5 Processor requirements

Second-generation star trackers require large computational resources to do the initial attitude acquisition and calculate the quaternion of the image data at high frame rates. The two leading examples [10, I 1], track, perform pattern recognition of the star constellations in less than 2 seconds. The tracking update rate depends on whether special electronics operate the CCD in a "windows mode" or the microcomputer has to digitize the whole image and handle all image processing by itself. Update rates for star trackers are on the order of 1-30 Hz. A processor in the 10 to 15 MIPS range is required.

5.6 **Analog-to-digital converter (ADC) resolution**
'1'here is a large span in brightness between the dimmest and the brightest star detected. In order to preserve information, it is desirable to employ a high-resolution, 12-bit ADC. However, when a large number of stars are utilized in the star image (>50), only a small fraction of the stars are so bright that more than 8 bits are required. If only 8 bits are utilized, there is a large computational advantage. and the few very bright stars in the image can be discarded, since their contribution to overall accuracy is small.

5.7 **Update** rate
The update rate depends on two factors: the exposure time and the processing time for the image. These two processes may be pipelined. The longer the exposure time, the more photons are utilized and the better the signal-to-noise ratio. However, the entire attitude control subsystem relies on how accurately the attitude can be extrapolated to a specific time. Therefore, exposure time and accuracy are trade-offs for a stable platform, depending on the spacecraft dynamics. For a second-generation unit large computations are required between updates; this may very well be the limiting factor on frame rate. In the case of a spinning spacecraft, or even those experiencing, orbital angular rates, the exposure time is limited because the stars will be smeared out over a large track with an effective loss in sensitivity and accuracy.

6. ACCURACY

The fundamental limit of pointing accuracy of a star tracker is the knowledge of star positions which are the most accurate references available. Astronomers have spent hundreds of years recording star positions. The HIPPARCOS [22] star catalog recently (mid '97) became commercially available. The objective of the HIPPARCOS satellite was to record the 120,000 brightest stars with a positional accuracy of 1 milliarcsec, thus, effectively eliminating star position uncertainties from the error budget of general-purpose attitude determination.

Star trackers are capable of accuracies in the range of 0.1-20 arcsec. It should be noted that it is common to quote accuracy in rms (or 1 σ), not 3 σ values. Pitch, yaw, and roll values are specified about the boresight of the optical axis. The following is a discussion of how the accuracy is achieved, its components, and its measurement:

The angular resolution of a single pixel is not that high, but utilization of two phenomena will increase it:

- Sub pixel accuracy which can be achieved by calculating the star image centroid
- Utilization of multiple star observations in each image

6.1 Sub pixel accuracy
It is essential to not have highly resolved, or sharp, star images. The images must be spread over several CCD pixels. Thus, it is possible to determine the position of the star by calculating the center of the whole image (the centroid) and interpolating to a small fraction of one pixel [23]. Resolutions down to 1/100 pixel have been achieved. On the other hand, it is not desireable to smear the star out on too large an area, because this will decrease the SNR. Typically, a point spread function of a few pixels is chosen. For illustration purposes, Figure 7 shows a star image from a developmental star tracker taken in early 1997 and includes a close-up of a single star and the calculated star centroid.

If it is possible to mount the CCD orthogonal to the axis of rotation and use a frame transfer CCD in time delay integration (TDI) mode, the adverse effect on accuracy can be minimized. This means that the images are read out in the opposite direction of the motion of the satellite, and the photoactive area, therefore , is fixed in space, which provides significant compensation. A motion smear reduction factor of 14 to I is expected in one study. It is also possible to determine a rough estimate of the axis of rotation and spin rate by utilizing image processing on an image acquired in the tumbling mode.

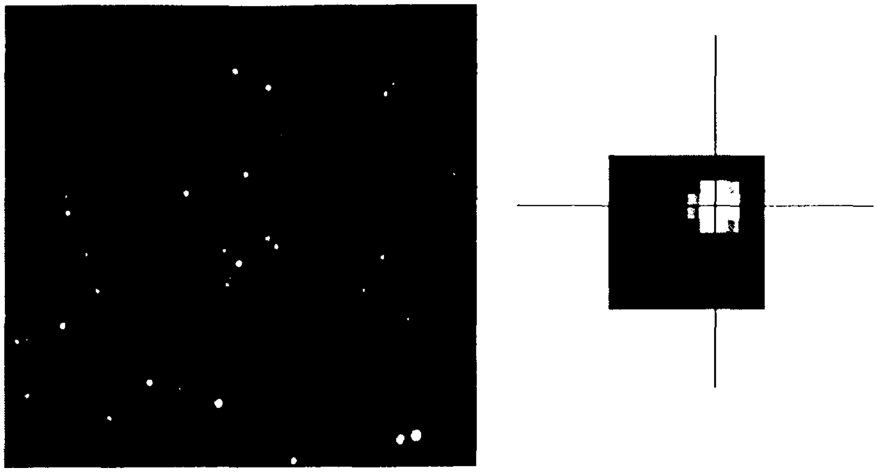

Figure 7. Star image acquired with an Active Pixel Sensor (AI'S) based JPL prototype star tracker. To the right is shown a close-up of a single star and the calculated centroid as indicated by the cross hairs.

6.2 Multiple stars

Based on either the previous attitude estimate or the pattern recognition of star constellations algorithm (which is only rarely applied), it is known **which stars in the star image corresponds to which on the firmament. Various star coordinate systems** can be used, typically .12000 [24] is used. This can be corrected for precision, nutation, and light time aberration (provided the trajectory is supplied). The star catalog position is projected onto a unit sphere. A right-hand VSN (vernal, summer, north) coordinate system can be used [25]. The X-axis pointing towards the vernal equinox and Z-axis pointing toward the North Pole.

A star catalog star with right ascension (α) and declination (δ) will map onto:

$$\hat{V} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\delta \ \cos\alpha \\ \cos\delta \ \sin\alpha \\ \sin\delta \end{bmatrix} \tag{2}$$

The stars in the CCD image are also projected onto a CCD unit circle, e.g., X- and Y-axis coincident with the CCD chip and Z-axis pointing orthogonal toward the star. If a star has position (x,y) on the CCD chip, the angular distance to the boresight (ϕ) will be:

$$\phi = \arctan \frac{\sqrt{(x - x_0)^2 d^2_{horizontal\,pixel\,size} + (y - y_0)^2 d^2_{vertical\,pixel\,size}}}{F} \tag{3}$$

Where, $d_{horizonal\,pixel\,size}$ is the width of a single pixel in mm, $d_{vertical\,pixel\,size}$ is the height of a single pixel in mm and F is the focal length of the lens in mm, (x_0, y_0) is the intersection of the CCD chip and the optical axis.

Typically, the lens will cause some distortion, which is corrected for by utilizing a lens distortion correction polynomial:

$$\phi_{corrected} = a_1\phi + a_2\phi^2 + a_3\phi^3 + a_4\phi^4 + \ldots \tag{4}$$

The lens distortion coefficients $(a_1, a_2 \ldots)$ are determined by the lens manufacturer or by calibration.

The argument (0) of the star observation is:

$$\theta = .4\tan 2\left((y - y_0)\, d_{vertical\ pixel\ size}(x - x_0)\, d_{horizontal\ pixel\ size}\right) \quad (5)$$

Where Atari? is four quadrant arctan, and $0 \le \operatorname{atan2}(y,x) \le 2\pi$.

Now the star maps onto the unit sphere:

$$\hat{W} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} \cos\theta \sin\phi_{corrected} \\ \sin\theta \sin\phi_{corrected} \\ \cos\phi_{corrected} \end{bmatrix} \quad (6)$$

The star tracker should calculate the best "average" rotation, which rotates star catalog positions $(\hat{V})$ on the unit VSN sphere to the star observations $(\hat{W})$ on the unit camera sphere. In other words, minimize:

$$\sum_{i=1}^{N_{stars}} \left|\hat{W}_i - A\hat{V}_i\right|^2 \quad (7)$$

The problem of deriving an average direction cosine/quaternion for an over-determined set of equations has been solved by the Quest algorithm [26].

The accuracy of the solution will depend on the accuracy of the single stars and the number of stars utilized in the following way:

$$Error_{star\ frame} = \frac{Error_{single\ star}}{\sqrt{N_{stars}}} \quad (8)$$

Typically, the twist angle will be 4 to12 times less accurate than those of the pitch and yaw. The twist angle primarily depends on the number of pixels on the CCD and the accuracy of the subpixel algorithm.

All of the terms which contribute to a single star error, can be compiled in an error tree or budget as shown in Figure 8. Measurement of accuracy is challenging. Starting with the noise equivalent angle (NEA) which is the variation of the attitude estimate when the star tracker is presented with a constant input, the NEA **can be measured by mounting the star tracker on an equatorial mounted telescope. The telescope is commanded to track a portion of the sky near zenith.** The output of the star tracker should remain constant, and only include the NEA. The noise of the telescope drive and atmospheric perturbations are superimposed on the attitude estimate. It should be noted that it is desirable to utilize a premium observation site with a high accuracy, low noise tracking system, because the magnitude of the atmospheric perturbation typically is comparable to the NEA of the star tracker. An example of the output of a second generation, prototype star tracker, the Advanced Stellar Compass (ASC) from the Technical University of Denmark is depicted in Figure 9. The data were acquired at Mauna Kea, Hawaii, in May 1996 with seeing conditions in the range of 0.3 arcsec, rms. It shows the declination and the roll angle outputs.

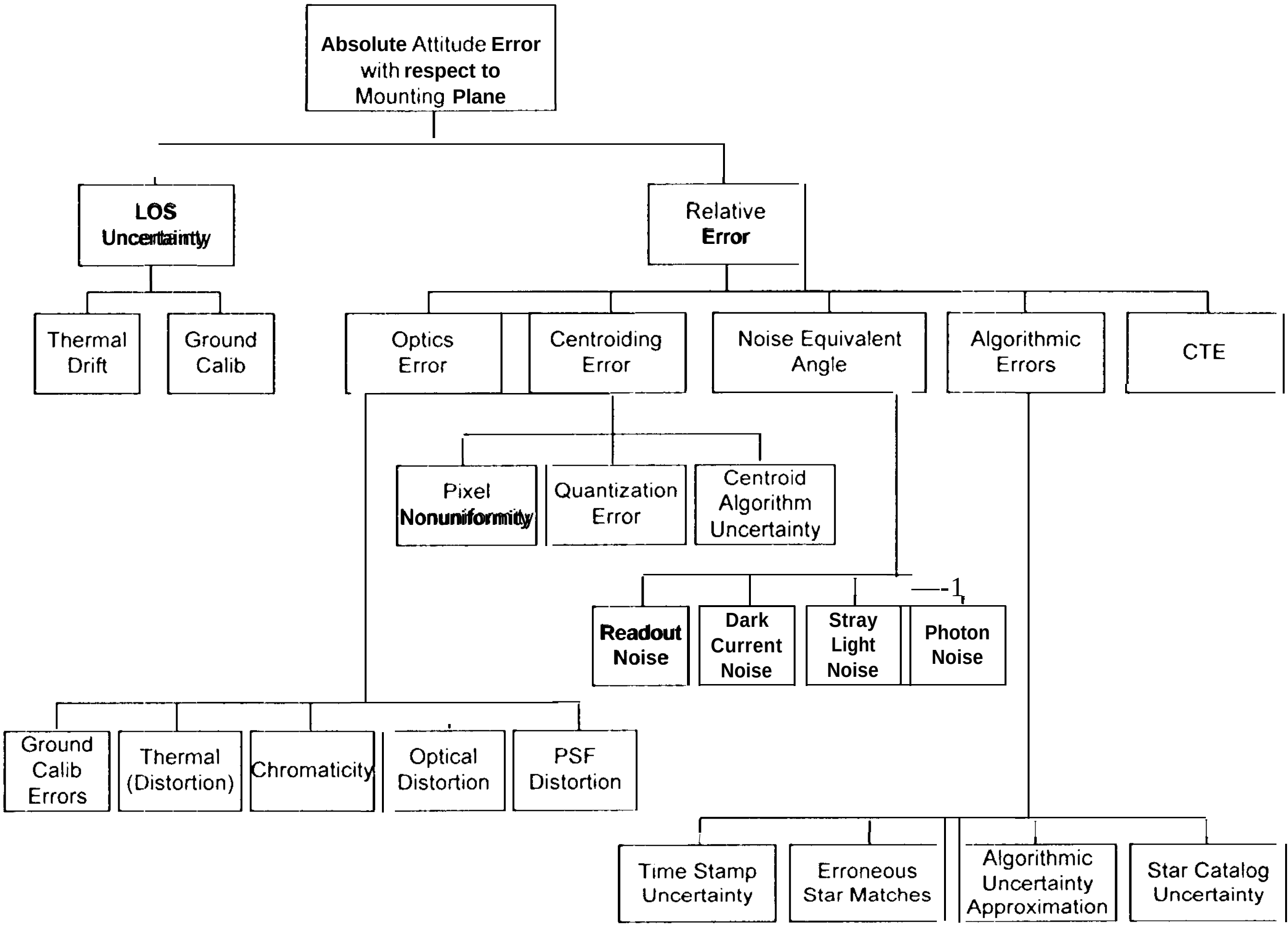

Figure 8. Single star error budget

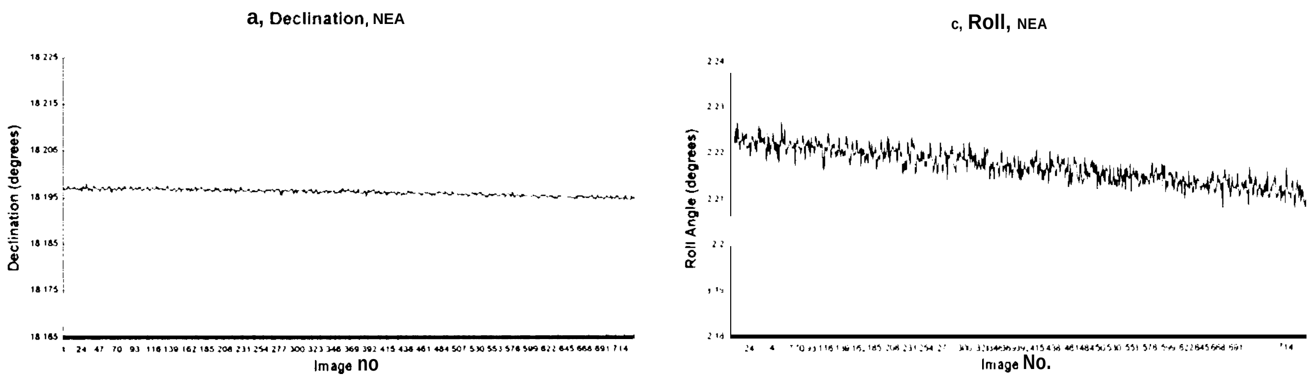

Figure 9. NEA measurement of the prototype ASC. The values are 1.1 arcsec in declination and 8 arcsec in roll angle, both rms, when low frequencies due to observation artifacts are removed.

It is also possible to measure the relative accuracy of a star tracker with a real star field. Relative accuracy is defined here, as the uncertainty in the positional output that occurs while the star tracker FOV is presented with moving star fields. This uncertainty includes all of the error terms, except the line-of-sight (LOS) offset terms. The relative accuracy of a star tracker can be measured by pointing the star tracker toward the zenith. During this operation the star fields drift though the FOV. The declination and roll rate will remain constant while the right ascension will drift with the sidereal rate in the FOV. Figure 10 shows the output declination and roll angles from the prototype ASC.

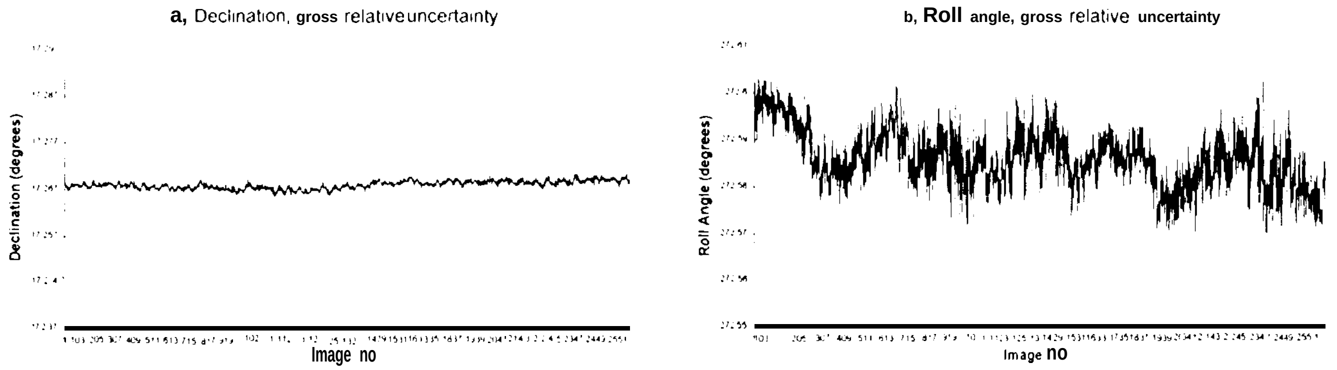

Figure 10. Declination and roll angles of the attitude estimate of the prototype model of the ASC. The relative accuracy of the declination is 1.4 arcsec and the relative accuracy of the roll angle is 13 arcsec, both in rms, when low frequencies due to observation artifacts are removed.

All of the measurements and error budgets discussed have assumed that the star tracker was mounted on a three-axis, stabilized spacecraft with negligible, motion-induced smear. Normally, there will be some motion-induced smear which will reduce the accuracy. A good quantization of this effect is not readily available, but it is common to specify accuracies up to some limiting rate such as 0.1 degrees per second.

7. FUTURE DEVELOPMENTS OF STAR TRACKERS

Star trackers have undergone a significant evolution in the past five years; an even faster pace of evolution is anticipated in the next five years as a result of ongoing developments in sensors and microminiaturization.

All star trackers discussed herein are based on the mature CCD area array sensor technology. A competitive, new, sensor technology field has appeared: active pixel sensors (APS) [27,28]. APS advantages over CCDs include enhanced radiation resistance, a larger dynamic non-blooming range, and control of individual pixel integration times. However, APS technology is not yet mature. Preliminary, real sky tests conducted at JPL shows promising results in star tracker applications. The APS sensor requires no special support chips, since it is fabricated using standard CMOS technology. Therefore, supporting logic and parallel analog-to-digital (A/D) encoding can be integrated with it on a single piece of silicon. It also operates from a single 5-volt supply. These factors make it very compatible with microcontrollers and the eventual realization of a single IC star tracker whose mass and size are dominated by the optics and baffle. Such a high level of integration also promises great reductions in cost and a large increase in the number of applications.

The hardware demands for both present and future versions of a second generation star tracker can be generally summarized as follows

- Small f/no optics
- 5-30 degree FOV
- Solid state, area array
- 10-15 MIPS computer with A/D conversion
- Few Mbytes memory
- Few Mbytes FLASH RAM memory
- Communications interface

Current state-of-the-art microcontrollers designed for hand held devices [29,30] can meet all of the hardware requirements with 4 to 5 ICs for the entire star tracker, if an APS sensor is utilized. Furthermore, the ICs can be stacked together in one package. It is believed that this existing technology can realize a second-generation star tracker weighing 200 grams and consuming 400 mW. Currently, NASA funding is expected for a joint JPL/Goddard Space Flight Center star tracker initiative, working towards this goal.

The future combination of a second-generation camera head with a global position satellite (GPS) receiver for low-Earth orbital applications is attractive for obtaining both precision position and pointing information. The GPS receiver is also a small instrument equipped with a powerful microcomputer. It is possible to combine these instruments so they can utilize a common microcomputer. once such a navigation instrument is developed, it would be very easy to integrate with a satellite, and all navigation would have been taken care of. Such a device is proposed for a JPL future space interferometer mission, but to be used with a local beacon, instead of the standard GPS system.

In principle, a second-generation star tracker is a camera and a dedicated image processor. This combination has also many other applications in space, such as optical navigation, non-stellar object detection, space docking, formation flying, etc. [31]. Some current development is focused on having the star tracker operating, even though a majority of the FOV is occluded by the Earth or moon (with reduced accuracy). This will significantly increase the sky coverage enormously for Earth-orbiting applications.

8. SUMMARY

Star trackers have been rapidly evolving over the last half decade. First-generation devices output only a few star positions in CCD coordinates, whereas recently developed, second-generation units output their attitude referenced directly to the celestial sphere, and with increased accuracy. Various key numbers associated with a star tracker and how they affect the mass and the accuracy have been discussed, Pointing accuracy and field of view are mutually proportional and inversely proportional to mass. The key components of accuracy and examples of how accuracy is measured at astronomical observatories have been covered. Finally, it is projected that future star trackers will be even smaller and the electronics could be integrated into a single large scale integration circuit package. Mass would be approximately 200 grams and power consumption 400 mW.

9. ACKNOWLEDGMENTS

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